MASSACHUSETTS INSTITUTE OF TECHNOLOGY

HABITUATION TO NOVEL VISUAL VESTIBULAR ENVIRONMENTS
WITH SPECIAL REFERENCE TO SPACE FLIGHT

NASA GRANT NSG 2032

FINAL REPORT

1974 -- 1980

PRINCIPAL INVESTIGATOR: L.R. Young

CO-INVESTIGATORS: R.V. Kenyon
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I. INTRODUCTION

This research program was begun in 1974 to investigate the problems of disorientation and motion sickness in manned space flight. Its aims were to investigate both the etiology of space motion sickness (together with techniques for selection, training, habituation and treatment) and the underlying physiological mechanisms associated with spatial orientation in a bizarre environment. Human psychophysical experiments were seen as the basis for research concerning the interaction of visual and vestibular cues in the development of motion sickness. Particular emphasis was placed on the "conflict theory" in terms of explaining these interactions. Research on the plasticity of the vestibulo-ocular reflex was also planned as this reflex is undoubtedly involved in the habituation process. Experiments using prism goggles in both humans and animals were envisioned. Basic research on end organ function and the mechanics of the otolith were also carried out.

Background

Writings on "space sickness", both before the era of manned space flight and in more recent years, has concentrated on the vestibular problem alone. It has been discussed in terms of the "deafferentation" of the otoliths in the free fall situation of space flight as though they no longer provided any sensory information. Tests of habituation to weightlessness emphasized the otoliths alone or the interactions between otoliths and canals in tests such as those involving cross-coupled angular acceleration . The otoliths, of course, do continue to function during extended weightlessness, not only as indicators of transient linear accelerations of the head within the craft,

but also, at least in the early stages before habituation, as indicators that no change in head position with respect to any vertical reference was confirmed. The central theme of our research program is that consideration of the adaptation effects of one sensory modality alone is probably inadequate to understand the process of habituation. We emphasize therefore, not only the interaction between semicircular canal and otolith responses in unusual environments, but especially the relationship between the vestibular response and the changing visual field associated with passive and active head movements. The "conflict theory" considers that the major factor in the etiology of motion sickness is an unresolved conflict between spatial orientation information from the different sensory modalities. This conflict may be resolved either by eliminating or blocking out one or more of the channels (as in closing the eyes, eliminating head movements, or "concentrating on the instruments") or by a sensory rearrangement so that the various sensory channels yield data which is now found to be confirming rather than conflicting or incompatible.

The proposal originally chose five areas for study. These areas were:

Vestibular training

The use of visually induced motion sensation to produce a conflict and the training associated with resolving this conflict will be investigated experimentally. Using an appropriate visual display, sensations of motion can be induced in a stationary subject. This produces a conflict between the visual and vestibular channels. One area of possible exploration is the effectiveness of vertical linearvection in producing conflicting sensations such as might be experienced in free fall. The generation of an upward moving field produces a sensation of moving downward although no confirming otolith

signal appears. Similarly, changes in head orientation with respect to the vertical which have an associated change in a head-fixed visual surround can be used to create otolith-visual conflicts. We have demonstrated the successful transfer of habituation as measured by the vestibulo-ocular reflex from a purely visually induced motion effect using an optokinetic stimulus to a pure rotation stimulus. A similar transfer of habituation from visually induced roll to actual sensation of tilt appears to exist for changes in orientation with respect to the vertical. It is thus possible that some type of ground based training procedures might be used to habituate to the weightless condition.

Development of Personal Habituation Schedules

It was proposed that feedback of physiological measures and the provision of individual optical viewers might constitute a personal habituation schedule. Feedback in training is a well-established means of reinforcement. We plan to investigate the use of various physiological indicators, i.e. GSR, sweat rate, etc. for use in a feedback regime. The use of individual viewers is a more complicated and as yet untested idea. Basically, the viewers would present a conflicting stimulus to the wearer which would be used to hasten habituation to generalized conflict. The stimulus could be manipulated at will and thus could be strengthened or diminished according to a personalized schedule.

Improved Selection Methods using Habituation to Visual-Vestibular Conflict

Conventional testing for the selection of astronauts or flight training candidates involves eyes closed tests such as cupulograms or the ability to tolerate cross-coupled angular accelerations. If one assumes that the desired characteristic is the ability to habituate to a new environment, rather than the base level of physiological sensors, then a new set of tests for astronaut selection might be devised. These tests would be based, first of all, upon the subject's sensitivity to visual-vestibular conflict rather than to vestibular stimulation alone. For example, observing and measuring the manual tracking ability of a subject during true body motion and superimposed wide field conflicting visual information, we may be able to find a means for selecting between the extremes of the population with respect to tolerance of visual-vestibular conflict. Similarly, by pursuing the theory that the ability to resolve visual-vestibular conflicts is the basis for successful habituation to the spacecraft environment, we are led to propose another selection test based on habituation. By deliberately introducing a novel visual-vestibular environment, e.g. by use of Dove prisms, one might measure the speed of habituation and relate this to the candidate's likelihood of success.

Investigation of the Role of Gravity in the Coriolis Phenomenon

The preliminary results of the Skylab experiments left many unanswered questions about the role of gravity during head movement "Coriolis stimuli". It is clear from physical considerations of the semicircular canals that a rolling head movement produced during the long term angular velocity yaw rotation will produce a transient sensation of pitch. When performed in a laboratory on earth, this pitch

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sensation is not confirmed by either visual cues (if the eyes are open) or by graviceptor cues. The same head motion, performed in an orbiting spacecraft, would induce no conflicting otolith information in pitch (as well as no confirming roll cues). If the eyes were closed, no conflicting visual information would be generated. One might therefore expect increased tolerance to such movements, as was indeed the case in Skylab. Such evidence would lead to the conclusion that it was the ca al-otolith conflict which was responsible for motion sickness following such provocative head movements on earth, rather than the semicircular canal information itself. Such a conclusion is not supported by the alleged retention by the astronauts of their ability to make many such head movements on earth following their return from orbit. A general habituation to visual-vestibular conflicts may have been created during the period of weightlessness. Alternatively, specific habituation to the expected canal response may have developed during the repeated trials in weightlessness so that the reapparence of the canal-otolith conflict was tolerated relatively well. The precise explanation remains unclear. It is important, however, for an understanding of the basis of space sickness. We hope to investigate this phenomenon by the use of "pseudo-Coriolis stimuli" as mentioned above and by the possible utilization of caloric stimuli to produce a canal signal which is also in conflict with the otolith information.

These original areas of investigation were later modified, occasionally abandoned, and different approaches added as should be the case in any dynamic research situation. The major areas of investigation and their results are listed in the following sections.

II. MAJOR AREAS OF INVESTIGATION

Visual Vestibular Interaction

The objective of this research is to develop a functional model of how vestibular cues and moving peripheral visual fields act in concert to produce a perception of body attitude and a sensation of self-motion in humans. Derivation of such a functional model would be a significant contribution to both basic research in multisensory integration and to practical applications such as the motion sickness problem. Research would cover yaw motion about the vertical and then extend to the roll and pitch sensations. The experimental approach is to have a subject seated in a specially modified flight trainer (controlled through a computer and surrounded by a movable visual field) try to null the velocity he feels, which may be due either to actual movement of the trainer, circularvection, or some combination of the two. This approach will also be used with a linear acceleration device using combinations of actual linear motion and visually induced linearvection. These results will be used to model the way visual vestibular interactions are handled by the subject.

Ocular Counterrolling Measurement

Perhaps the only direct measurement of human otolith function is ocular counterrolling. Significantly, the measurement of ocular countertorsion is rarely performed in the clinical setting nor is it commonly done even in research on otolith function primarily because of the difficulties of instrumentation. The accepted method uses visual data processing by comparison of the orientation of successive color slides of the eye, taken with the head in various orientations relative to the vertical. This method

is time consuming, requires the use of repeated flashes and only yields a very limited amount of data at a time long after the experiment is completed. Some attempts at semiautomatic measurements have been made, but due to difficulties with the methods, they have not been widely adopted. We plan to investigate several alternative methods of measurement of ocular counter-rolling, each of which has the potential for delivering convenient on-line measurements. We propose to develop one or more of those techniques as a basis for our assessment of the effects of visual vestibular conflict, visually induced tilt and otolith function.

Spinal Reflex Responses to Linear Acceleration Cues

The synthesis and effects of descending motor commands to the segmental level is highly dependent on the state of segmental activity. For example, vestibular commands to the spinal cord travel over different pathways and have different effects on motor patterns depending upon whether the limbs are in flexion or extension phases of motion. To investigate the synthesis of otolith-spinal motor commands requires more than a simple standing paradigm can offer and a posture platform would require a prohibitive number of degrees of freedom for each leg in order to provide useful data. An alternative approach using EMG responses to sudden falls and possibly other types of linear accelerations my provide greater insight into the synthesis of otolith dependent motor responses. The presence of stereotyped EMG responses to sudden, unexpected falls, quite distinct from the functional responses occurring prior to the expected moment of contact have been demonstrated. The initial soleus EMG, or startle response, is otolith dependent, as shown by experiments with labyrinthine defective patients. It has been shown that both the startle response and the pre-contact EMG timing depend on the

magnitude of the acceleration. Thus, if these responses are used as a measure of otolith induced spinal activity, a number of more general issues may be attacked, such as the modifiability of the responses after release and the effects on on-going motor activity. The equipment envisioned for these experiments involves a device for suspending the subject, a counter-force to provide accelerations less than 1 g, a movable visual field, and a suitable landing surface, in addition to the EMG processing equipment. The first set of experiments would involve combined acceleration of the subject and the visual field as background for our work on unusual otolith-visual cue arrangement. While the startle reaction seems to require an intact vestibular system, visual information may still effect the magnitude of the response, considering the significant visual input to the vestibular nuclei. For example, dropping the both the subject and the visual field might decrease the startle response magnitude. Next, the modifiability of the pre-contact EMG timing can be determined by applying non-uniform acceleration during a fall. Subject ability to use additional otolith information after the moment of release can be determined by applying a series of steps in acceleration, or a ramp acceleration. Two issues are of importance: (1) whether the acceleration or the derivative of the acceleration is more important for determining the response and (2) the determination of an otolith-to-spinal latency, such that after a certain time prior to contact, otolith cues can no longer modify the response timing. By superimposing static postures on on-going movements as the sudden release occurs, the EMG patterns will indicate how vestibulo-spinal influence is distributed to the flexors and extensors of each limb during such activity. The results of this experiment may also be important in understanding the usage of otolith cues during locomotion.

Physiological Measurements Associated with an Early Endpoint for Motion Sickness

Nearly every researcher involved in the study of motion sickness has at one time or another considered purely physiological measures which would provide a reliable indication of the onset of motion sickness prior to the development of severe malaise or vomiting. Among the many methods which have been considered have been assessments of galvanic skin resistance, peripheral blood flow, sweat rate, breathing rate, and the variability of these rates. In addition, such "symptomatic measures" as gastric activity (electrogastrogram) have been utilized. No single physiological measure has proved to be a satisfactory or unique indicator of the onset of motion sickness and, as a result, most investigators have adopted one form or another of subjective evaluation with or without the use of a trained observer. The apparent success of biofeedback in attacking at least some of the symptoms of motion sickness leads us to reconsider the question of the physiological monitoring of an early endpoint. Apparently, although no single physiological measure may suffice, we may be able to use a combination of measures as the best predictor of the onset of motion sickness and, consequently, make on-line predictions which would allow us to terminate the experiments long before the level of nausea was actually reached.

Monkey Vestibulo-Ocular Plasticity

A more basic line of research involves the study of vestibular habituation mechanisms in a primate, specifically the Rhesus monkey. It has been shown that the wearing of reversing prisms for long periods of time results in some modification of the vestibulo-ocular reflex, adpating this reflex to the new environment. This has been demonstrated in the human using left-right

reversing prisms (head movement to the left causes visual field movement to the left, rather than to the right as normally occurs). We plan to experiment with cross-axis reversals (prisms such that lateral movement of the head causes vertical movement of the visual field and vice versa) to test the limits of the plasticity of the vestibulo-ocular reflex. Demonstration of adaptation across axes would be a non-trivial extension of the previous work, since there are no demonstrated pathways from the vertical semicircular canals to the horizontal recti. A positive result would suggest lesion studies to help isolate the sites of the plastic changes. Simultaneously we will observe the time course of habituation to this novel environment in an attempt to generate useful information for speeding up the habituation process for man in a bizarre environment such as weightlessness.

III. RESULTS

Visual Vestibular Interactions

Using the method of closed-loop velocity-nulling and a describing function analysis, a model has been built up which shows the importance of different types of cues. Beginning with a series of experiments in yaw, relationships were first derived for the manner in which visual cues effect vestibular thresholds and latencies. These results were then extended in scope by an experiment which provided for presentation of conflicting simultaneous independent pseudo-random visual and vestibular motion cues. This approach allows for the analytical determination of a dual-channel describing function model. Since the model proposes that both cues are processed independently,

and linearly summed to provide a central measure of motion sensation, it has been possible to demonstrate the limitations of the complementary linear filter hypothesis. A simple frequency separation of cues conflicts with the more complicated describing functions arising from the experimental data. The resulting linear dual channel model does, however, provide a standard against which other proposed functional models can be evaluated. Anly linear model is also in conflict with previously reported non-linear dynamic responses to combined cue stimulation, in both neurophysiological and psychophysical studies. To resolve this difficulty, extensive studies have been conducted to test the appropriateness of various simplified non-linear functional models based on the cue-conflict hypothesis. One particular model, which weights vestibular cues more heavily as cue disparity increases, appears to be a good candidate for explaining both the current experimental results and past studies in visually induced motion illusions.

This work has been presented in Zacharias (1977), Zacharias and Young (1981), Huang (1979) and Huang and Young (1981). Additional reviews of our visual vestibular activities (Young, 1978; Young, 1980) and an updated statement of our findings on pursuit eye movements (Young, 1977) and saccadic eye movements (1981) were prepared.

Ocular Counterrolling Measurement

We have investigated several alternatives to the photographic method for the measurement of ocular counterrolling. These have included:

(1) A television method, similar in concept to the standard photographic method commonly used, but using a still photograph of the eye in the reference position and video tape pictures of the eye taken continuously during head tilt. The video tape signal would be available for computer image processing using a maximum correlation technique. The concept we have in mind is that video tape signals of the eye in the test position would be compared, frame by frame,

with a video tape of the reference photograph, taken through a rotatable Dove prism. Using a hill climbing technique to maximize the cross-correlation of the two signals, the Dove prism is rotated until the image of the reference photograph is in the best possible angular orientation for a match with the test frame. Some manual intervention may be necessary to center the pupil in the test frame relative to that of the reference frame in the event of eye movement. Clearly the use of television will mean a reduction in resolution relative to high quality 35 mm photography, but this loss may be acceptable in view of the greater data rate of 60 fields per second with the TV system. Our preliminary experiments on image quality have used a low light level TV system and infrared illumination.

(2) Measurement of ocular counterrolling using the four electrode EOG system. The contribution of ocular counterrolling to signals picked up from horizontal and vertical electrodes during electro-oculography has been previously reported. The basic explanation for this phenomenon is that the corneo-retinal dipole, which serves as the basis for EOG, is aligned not with the optic axis, but rather with an axis running from the mid-point ofthe cornea to the optic disc and thus is displaced by 15 degrees from the fixation axis. As the eye rotates about the fixation line in countertorsion, the component of the corneo-retinal potential picked up by the horizontal and vertical electrode pairs differs. By appropriate, though difficult, calibration of electrodes, it is therefore possible to measure ocular counterrolling using EOG. This method has not been widely used, presumably because of the difficulty of electrode stabilization and calibration. However, with the use of our automated calibration technique, we may be able to make this a practical method for continuous monitoring of ocular counterrolling.

(3) Use of landmarks on soft contact lenses. Many of the objections to using a contact lens with thick lines as identifying marks for measurement of ocular countertorsion may be overcome if the newer soft or semi-soft contact lenses are used. Preliminary experiments indicate that the lens may be rendered totally adherent to the cornea with little or no discomfort to the subject. Several alternative methods for marking the soft lenses have been tried with varying degrees of success. We have tentatively decided on the fairly simple method of cutting a notch or strip from the lens. These cuts can be made with a scalpel and are both clean and clear. The boundaries can be made extremely distinct by using standard ophthalmological dyes. We have made preliminary attempts to utilize commercially available CCD image sensors in conjunction with these marked lenses. This technique is appropriate for use in dynamic, visually noisy environments, and is thus admirably suited for use in viewing a line against the background of the human eye. An optical system would focus an image of the eye on the CCD array. The array is scanned by an edge detector system, the output of which is then digitized, encoded, condensed and read into our PDP 11 computer. At this point, trigonometric comparisons will be made to achieve a total angle of rotation of the contact lens image and thus of the eye.

(4) A feasibility analysis of automatic data processing of film records of ocular counterrolling was performed in conjunction with Goodyear Aerospace Corporation. Although feasible, such a system is at present time prohibitively expensive.

For the present, we have relied on an improved photographic technique which utilizes a motor driven 35 mm camera which can take photographs at the rate of 3 frames per second. The subject is fitted with a biteboard with fiduciary marks aligned near the eye. This provides a head fixed reference system. A cloud chamber scanning device and improved computer processing complete the system. This system is used both for our general otolith experimentation and also as a point of comparison for the evaluation of alternative systems.

More complete discussion of this work can be found in the thesis of Edelman (1979), Young et al. (1980), and Edelman and Oman (1981).

Otolith Function Experiments

The postural tests of otolith function which are now part of our pre- and post-flight test procedures for Spacelab were frozen and include eyes open and eye closed static sway and response to unexpected pitching of the platform. Sway and EMG are recorded. The apparatus is currently being used in a separate project at the Gait Laboratory of Children's Hospital Medical Center to investigate the relationship between vestibular disorders and idiopathic scoliosis.

Spinal Reflex Responses to Linear Acceleration Cues

The major activity on postural otolith function tests involved an extensive set of experiments in which subjects were dropped unexpectedly at different acceleration profiles and in combination with moving wide field visual scenes which could confirm or conflict with the vestibular sensation. Analysis was done on the basis o. EMG recordings from five muscle groups and are discussed in Wicke (1980) and Wicke and Oman (1980).

Human subjects were suspended in a safety harness 17 inches above the floor by a steel cable connected to a computer controlled force generator (magnetic particle brake). After the subjects were unexpectedly released, various controlled patterns of downward acceleration (less than 1 g) could be produced. During the falls, EMG activity was recorded simultaneously from the gastrocnemius, soleus, tibialis anterior, rectus femoris, and biceps femoris, along with knee and ankle joint angle in one leg. Subjects were tested eyes closed and eyes open, both in darkness and in light using a wide field visual disply. The display scene could be moved downwards at exactly the same velocity as the moving subject, left fixed with respect to the laboratory ("normal visual field"), or moved upwards at a speed equal to the subject's falling velocity ("upward moving visual field"). Ten vestibularly normal subjects each underwent a total of 45 drops, experiencing three replications of each vision/motion combination used. Under normal visual field conditions, both short and long latency EMG responses were seen, which were dependent on the magnitude of the acceleration stimulus. Certain of the visual conditions significatnly altered both the short and long latency responses in most of the muscles tesed. Effects were particularly prominent in the gastrocnemius and soleus, and were also more pronounced during slow (0.5 g) falls. The

upward moving visual field condition increased the short latency EMG reaction in gastrocnemius and soleus. A preliminary model for visual-vestibular interaction in short latency EMG responses is being prepared.

Motion Sickness

We developed and tested a photoplethysmograph for measurement of facial pallor and sweating and experimented with an electrogastrogram. Neither showed immediate promise as an early end point detection instrument. The use of reversing prisms on subjects free to make active head movements and to walk proved to be a very rewarding step in the investigation of motion sickness. Oman and Bock were successful in using a motion sickness rating scale to track the dynamics of motion sickness symptom development and recovery. Oman extended the sensory conflict model for motion sickness development significantly by placing it in the context of an optimal filtering problem and using the notion of an internal model and expected response based upon active movements (Oman, 1978; 1980).

Plasticity of the VOR

We completed our planned program of investigating the limits of VOR plasticity in the monkey by creating a situation in which transfer of the vestibulo-ocular reflex would have been required. In the monkeys investigated, no such cross-axis adaptation was shown, despite several months of exposure with Dove prisms rotated at 45° such that horizontal head movements invoked vertical field movement (Greene and Young, 1979; 1981). These results would support the notion of organization of postural, or at least oculomotor, reflexes along planes of the semicircular canals; they may be in conflict

with reported results in humans and in cats.

IV. SUMMARY

Over the course of this grant, significant progress has been made in both the basic understanding of sensory processing with respect to visual and vestibular interaction and in our understanding of the problem of motion sickness. Adaptation to unusual environments has been studied. Useful tools for measurement of ocular torsion and motion sickness symptoms have been developed. Mathematical models for visual vestibular interaction and motion sickness have also been developed. A battery of different tests have been organized and used in our pre-flight testing on the Spacelab 1 crew. The efficacy of these tests as motion sickness or habituation predictors will not be known until much later, but the baseline data has been collected. The work begun under this grant is continued under NAG 2-88.

V. PUBLICATIONS

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